

X-ray testing Constellation-X optics at MSFC's 100-m facility

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ABSTRACT

As NASA's next facility-class x-ray mission, Constellation X will provide high-throughput, high-resolution spectroscopy for addressing fundamental astrophysical and cosmological questions. Key to the Constellation-X mission is the development of lightweight grazing-incidence optics for its Spectroscopy X-ray Telescopes (SXT) and for its Hard X-ray Telescopes (HXT). In preparation for x-ray testing Constellation-X SXT and HXT development and demonstration optics, Marshall Space Flight Center (MSFC) is upgrading its 100-m x-ray test facility, including development of a five degree-of-freedom (5-DoF) mount for translating and tilting test articles within the facility's large vacuum chamber. To support development of alignment and assembly procedures for lightweight x-ray optics, Goddard Space Flight Center (GSFC) has prepared the Optical Alignment Pathfinder Two (OAP2), which will serve as a surrogate optic for developing and rehearsing x-ray test procedures. In order to minimize thermal distortion of the mirrors during x-ray testing, the Harvard-Smithsonian Center for Astrophysics (CfA) has designed and implemented a thermal control and monitoring system for the OAP2. CfA has also built an aperture wheel for masking and sub-aperture sampling of the OAP2 to aid in characterizing x-ray performance of test optics.

Keywords: X-ray telescopes, optics testing, x-ray astronomy

1. INTRODUCTION

Constellation X¹ will be NASA's next facility-class x-ray mission, following the highly successful *Chandra* X-ray Observatory^{2,3}. As one of the cornerstones of the recent "Beyond Einstein" initiative, Constellation X will provide high-throughput, high-resolution spectroscopy of cosmic x-ray sources to probe regions of strong gravity, map dark matter, study the life cycle of matter in the universe, and address other outstanding issues in high-energy astrophysics. NASA Goddard Space Flight Center (GSFC) manages the project and leads the mission development with the Smithsonian Astrophysical Observatory (SAO) and other partners. NASA Marshall Space Flight Center (MSFC) is supporting the project development, including x-ray testing of optics and science instrumentation. Currently, MSFC, GSFC, SAO, and other partners are preparing for initial testing of Constellation-X development optics at MSFC's 100-m x-ray test facility.

Here we describe activities to prepare the facility and test equipment for x-ray performance testing of Constellation-X development optics. We begin with brief overviews of the Constellation-X mission (§2) and of MSFC's x-ray test facilities (§3). Next we describe the x-ray test system at the 100-m facility (§4) to be used for initial characterization of Constellation-X development and demonstration optics. We conclude with a summary of test plans (§5).

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2. CONSTELLATION-X MISSION

The Constellation X-ray Mission¹ will utilize four identical spacecraft, orbiting near the Earth–Sun second Lagrange (L2) point. Slated to become operational in the middle of the next decade, each satellite will constitute a multiple-telescope observatory. In Section 2.1, we briefly describe the x-ray observatory; in Section 2.2, we provide a few more details about the observatory’s large x-ray optics.

2.1 Constellation-X observatories

Each Constellation-X observatory (Figure 1) will include one (1) Spectroscopy X-ray Telescope (SXT) and three (3) Hard X-ray Telescopes (HXTs), spanning collectively the energy range 0.25–60 keV. The SXT will comprise a large (1.6-m-diameter) mirror assembly, with thermal pre- and post-collimators; a reflection-grating assembly (RGA), partially covering the optics’ exit aperture; a cryogenically cooled, pixilated microcalorimeter at the SXT optics focus; and a charge-coupled device (CCD) RGA read-out array. Each HXT will have a 0.4-m-diameter mirror assembly and a pixilated hard-x-ray detector (e.g., cadmium–zinc–telluride). In order to provide the large areas required for astrophysical x-ray spectroscopy while satisfying weight limits, both the SXT and HXT mirror assemblies utilize lightweight, highly nested, grazing-incidence mirror pairs. All four telescopes (1 SXT and 3 HXTs) will share a lightweight, stiff, optical bench that will afford a 10-m focal length for each x-ray telescope.

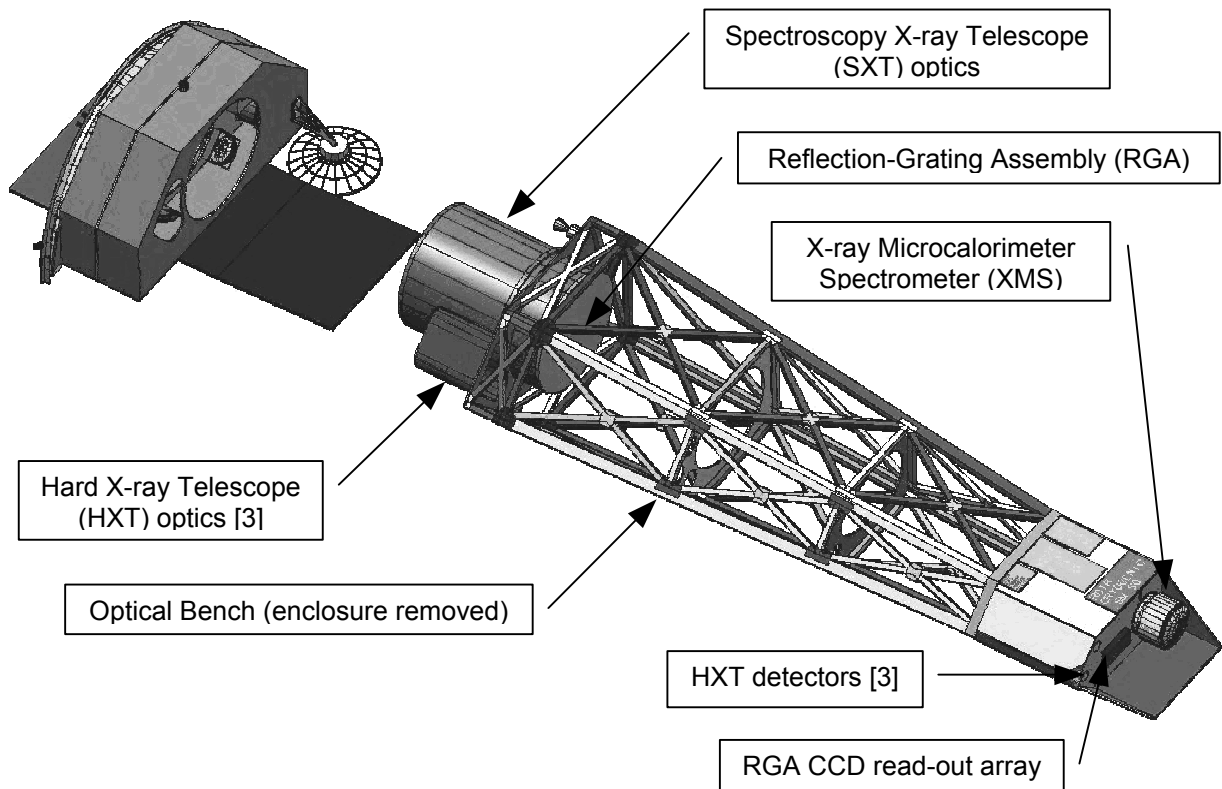
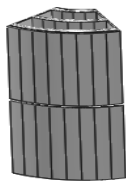


Figure 1 — Constellation-X design concept, for each of 4 identical x-ray observatories. The Spectroscopy X-ray Telescope (SXT) and the 3 Hard X-ray Telescope (HXT) mirror assemblies are densely nested, grazing-incidence x-ray optics with 10.0-m focal length. Outer diameters of the SXT and HXT optics are 1.6 m and 0.4 m, respectively.

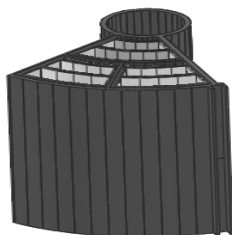
2.2 SXT optics

Key to the success of the Constellation-X mission is development of the SXT optics⁴. The mission's science requires that the SXT optics provide large effective area for gathering the photons necessary for high-resolution spectroscopy of cosmic x-ray sources, and good angular resolution (half-power diameter less than 15", with a goal of 5") to avoid source spectral confusion and to allow high-resolution dispersive spectroscopy with the RGA. On the other hand, the SXT optics must be lightweight to stay within its mass allocation. Recognizing the technological challenges in developing the SXT, the Constellation-X Project has laid out a roadmap leading from developmental optics, to an engineering unit, to a flight prototype unit, to the flight mirror assembly (Figure 2).

Engineering Unit



Prototype Unit



Flight Unit

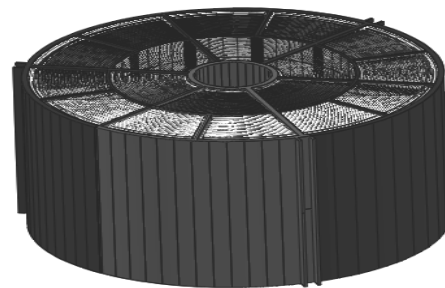


Figure 2 — SXT optics on technology roadmap. The Engineering Unit (left) is a sub-scale inner module of the Prototype Unit (center), which is a sparsely populated, 60° section of a Flight Unit (left).

Figure 2 illustrates the planned progression toward development of the SXT Flight Mirror Assembly. The Flight Unit will be a 10-m-focal-length, 1.6-m-outer-diameter mirror assembly, comprising 18 modules (6 inner and 12 outer) synthesizing 170–230, densely nested shells. Leading up to the Flight Unit, the Prototype Unit will be a full-scale 60° section of a Flight Unit, comprising 3 modules (1 inner and 2 outer) that are only sparsely populated (3–9 mirror pairs per module). Prior to the Prototype Unit, the Engineering Unit will be a sub-scale (8.4-m-focal-length, 0.5-m-diameter), sparsely populated (1–3 mirror pairs) version of the inner module.

Currently, GSFC is working on the Optical Alignment Pathfinder Two⁷ (OAP2, §4.3), a precursor to the Engineering Unit. The OAP2 serves a dual purpose: It is a test bed for developing alignment, bonding, and assembly procedures; and it provides a very stiff (not flight-like) housing for evaluating performance of developmental x-ray mirrors⁵.

Integral to the development of the SXT (and HXT) optics is a program of x-ray testing. At the initial stages, the purpose of the x-ray testing is primarily to measure the point spread function of the mirror assemblies. At intermediate stages, the x-ray test objectives will be to characterize more fully the performance — e.g., point spread function, effective area, off-axis response, etc. — of the mirror assemblies. The later stages of x-ray testing will be verification and calibration of flight mirror assemblies and instruments.

3. MSFC X-RAY TEST FACILITIES

The Marshall Space Flight Center (MSFC) operates two test facilities and associated equipment for testing space (x-ray and visible) optics and instruments. The premier facility is the X-Ray Calibration Facility (XRCF), used for verification and calibration⁶ of the *Chandra* X-ray Observatory, as well as for other space astronomy programs. In addition, MSFC operates the (smaller) “Stray-Light Facility”, most recently used primarily for testing MSFC-developed hard-x-ray optics and detectors. In Section 3.1, we give a brief overview of the XRCF, to be used primarily during the later stages of Constellation-X testing and calibration. In Section 3.2, we describe the Stray-Light Facility, which will be the venue for most of the early x-ray testing of the SXT and HXT development optics.

3.1 X-Ray Calibration Facility

The X-Ray Calibration Facility (XRCF) at MSFC is the world's largest facility built for testing x-ray optics and instruments. Originally constructed for x-ray testing the second High-Energy Astrophysical Observatory (HEAO-2, the

Einstein X-ray Observatory), MSFC substantially renovated the facility to support the verification and calibration of NASA's Advanced X-ray Astrophysics Facility (AXAF) — i.e., the *Chandra* X-ray Observatory. Subsequently, the XRCF continues to serve as an important facility for testing x-ray and infrared-visible optics and instruments — e.g., Solar X-ray Imagers (SXIs) for the NOAA Geostationary Operational Environmental Satellite (GOES) series, and developmental and demonstration optics for the James Webb Space Telescope (JWST; *nee* the Next Generation Space Telescope, NGST). The vacuum chamber has liquid nitrogen panels and heater panels to simulate a deep-space environment and to provide accurate thermal stability. More recently, to support JWST demonstration testing, the XRCF implemented several (visible-light) wave-front measuring devices and a sophisticated liquid-helium cryo-system (1-kW helium refrigerator and cryogenic shrouds), in order to achieve the low temperatures (about 35 K) needed for the JWST (infrared) mirrors.

With a 518-m-long guide tube (Figure 3, left), the XRCF provides a long (about 538-m) source–detector distance, which reduces the effects of finite source size and of beam divergence over the optics aperture. The XRCF's huge vacuum chamber (Figure 3, right) is 22.9-m long with a 7.3-m diameter; thus, it can accommodate any structure that would fit into the payload bay of a Space Shuttle Orbiter. In particular, the XRCF chamber allows testing optics of focal lengths up to 15 m (13 m, with current optics and detector tables). Because the diameters of the guide tube and primary gate valve allow full illumination of apertures up to about 1.45-m diameter, full-aperture testing of the Constellation-X SXT would require replacing the primary gate valve and some sections of the guide tube. Nonetheless, with the current guide tube, sub-aperture testing would still fully illuminate up to a 120° sector of the SXT.

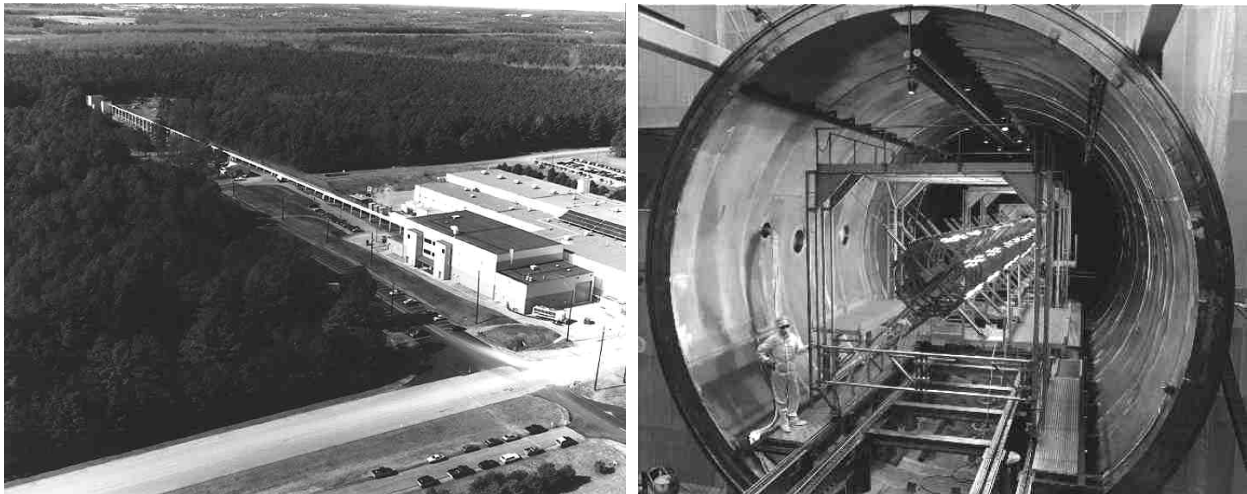


Figure 3 — The X-Ray Calibration Facility (XRCF) at MSFC. The left photo shows the 0.6-km extent of the XRCF from the x-ray source building on the upper left to the instrument-chamber building on the lower right. The right photo displays the large (vacuum) instrument chamber, prior to installation of tables and cryo-shrouds.

In that planning for Constellation-X x-ray verification and calibration has not yet begun, requirements for ground-support equipment (GSE) sources and detectors remain to be specified. Currently available x-ray sources at the XRCF include a fixed-anode (electron-impact) source, with interchangeable targets and selectable x-ray filters; two rotating-anode sources, each behind a monochromator (one with selectable double crystals, the other with selectable erect-field reflection gratings); and a Penning source, for producing low-energy lines. Multiple flow proportional counters and a solid-state spectrometer serve as beam-normalization detectors. Available at the focal plane are a flow proportional counter and solid-state spectrometer (each with selectable apertures) and a high-resolution microchannel-plate imager.

3.2 Stray-Light Facility

In addition to the 538-m-long XRCF, MSFC operates a 104-m-long (source–detector) x-ray test facility. Originally developed and still occasionally used for stray-light testing of visible-light optical systems, the so-called “Stray-Light Facility” (Figure 4) now serves primarily as a convenient and inexpensive facility for performance evaluation and calibration of x-ray optics and detectors. The facility can accommodate x-ray optics up to about 1-m diameter and 12-m

focal length. Currently available (electron-impact) fixed-anode sources at the facility span the approximate energy range 0.1 to 100 keV, thus supporting testing of soft- and hard-x-ray optics and detectors. Available MSFC detectors are a front-illuminated CCD (charge-coupled device) and a scanning CZT (cadmium–zinc–telluride, CdZnTe) detector, with low-energy cut-offs of about 0.8 and 3 keV, respectively. The Constellation-X Project and its partners will install additional detectors — including a (commercial) large-format back-illuminated CCD x-ray camera and a (CalTech-provided) pixilated CZT detector — to enhance the testing capabilities for both soft- and hard-x-ray optics.



Figure 4 — The 100-m Stray-Light Facility at MSFC. The left photo shows the approximately 90-m-long guide tube, emerging from the source building. The right photo displays the (vacuum) instrument-chamber domed soor. Because the guide tube enters the instrument chamber flush with its floor, detectors attach to a port near the bottom of the dome.

For various reasons, we intend to use the 100-m facility for most of the early Constellation-X x-ray testing of SXT and HXT development and demonstration optics. First, with minor enhancements now nearly complete, the Stray-Light Facility is quite sufficient for initial Constellation-X performance testing, which focuses primarily on measuring the point spread function of SXT and HXT optics. Second, we shall have good access to the 100-m facility during the critical development period, with only minor schedule contention with other programs. Furthermore, the smaller facility is simpler and more economical to operate. Of course, the Stray-Light Facility lacks some features and capabilities of the XRCF, which we intend to use for later testing, verification, and calibration.

4. X-RAY TEST SYSTEM

During 2004, we shall begin testing of both SXT and HXT development and demonstration optics at MSFC's 100-m facility. Because of the greater demands — e.g., angular resolution, mass, and complexity — of the SXT performance testing relative to that of the HXT, the SXT has driven the test requirements. Consequently, we here concentrate our discussion on the x-ray test system for characterizing the first SXT development optic, the Optical Alignment Pathfinder Two⁷ (OAP2).

Figure 5 summarizes the primary subsystems of the 100-m-facility x-ray test system, as configured for rehearsing test procedures and conducting initial x-ray testing of the SXT development tool, the OAP2. In the remainder of this section, we briefly address each of the x-ray test subsystems — the Facility (§4.1), the Mount (§4.2), the Optics (§4.3), the Source (§4.4), the Detector (§4.5), and the Data (§4.6) subsystems.

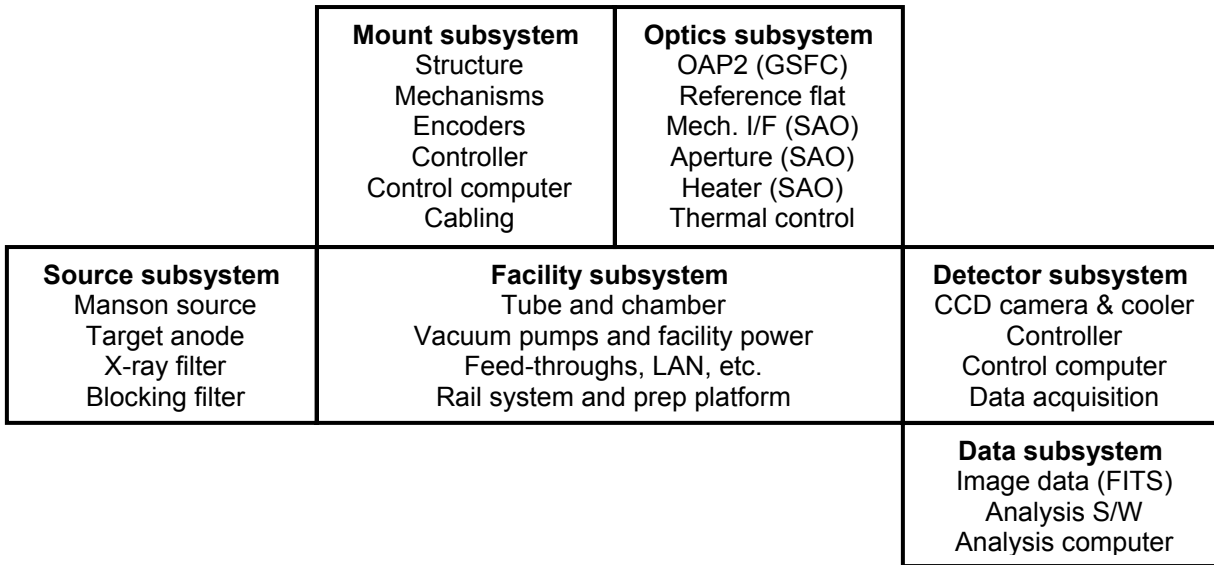


Figure 5 — Block diagram of x-ray test system for rehearsal and testing of the initial Constellation-X SXT development optics. Test subsystems are the Facility, Mount, Optics, Source, Detector, and Data.

4.1 Facility subsystem

The Facility subsystem comprises the guide tube and instrument chamber, vacuum pumps, electrical feedthroughs into the chamber, and a preparation platform and rail system for moving equipment into and within the chamber. In addition, the facility provides electrical power, a local-area network (LAN), filtered air, and various preparation and storage areas. Although the instrument chamber tapers into the guide tube at the source end, its full 3.0-m diameter extends 12.2 m. The 1.2-m-diameter guide tube extends 89.3 m (including the tapered portion of the chamber) from the source. In the chamber's domed door, is a gate valve centered on the extended axis of the guide tube. This dome's gate valve allows attachment of a detector or extension of the vacuum length through supplemental tubes and flanges.

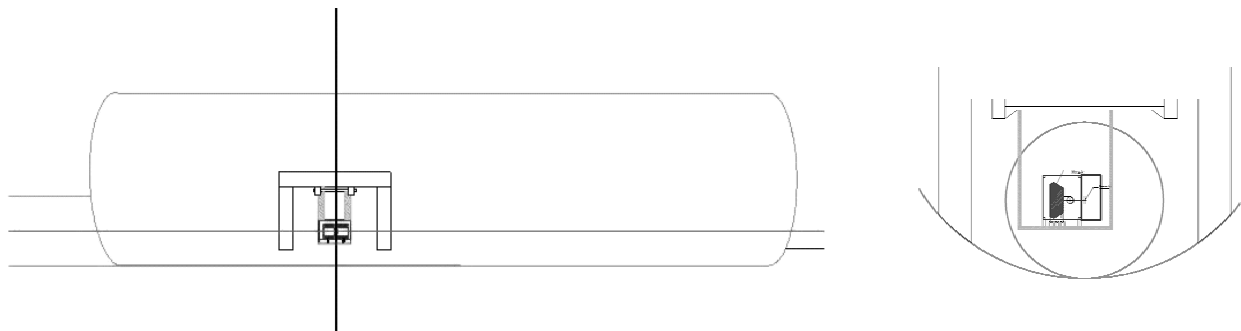


Figure 6 — Schematic drawing of the Stray-Light Facility's instrument chamber with the optics mount installed. The left panel displays the chamber from the side; the right panel shows the mount holding a test article, as viewed from the end of the chamber. Note that the bottom of the guide tube is at the level of the chamber's floor.

An awkward feature of the facility is the location of the guide tube with respect to the large vacuum chamber (Figure 6). Because the guide tube enters the chamber at the chamber's floor level, it is not possible to utilize fully the diameter of the tube for illuminating an optic. Thus, about 1-m diameter is the practical limit for illumination of a full-cylinder

object. In order to achieve this, it is necessary to support a large-diameter (≈ 1 m) optic from above. This constraint severely impacted the design of Mount subsystem (§4.2), substantially increasing its weight and complexity.

Unlike the XRCF instrument chamber, the 100-m facility's vacuum chamber lacks a thermal-control system. However, due to the large thermal inertia of the chamber and its location inside a thermally controlled building, the temperature within the chamber is typically rather stable at about 20° C. Nonetheless, the potential sensitivity of an optical system to thermal gradients and fluctuations may require active thermal control. Hence, SAO has designed and built a thermal-control system (§4.3), including a heater box enclosing the OAP2 from GSFC.

4.2 Mount subsystem

The most time-consuming and costly upgrade to the Stray-light Facility has been the Mount subsystem. MSFC designed and built a five degree-of-freedom (5-DoF) table as a facility-provided optics test mount. For maximum versatility and utility to the Constellation-X Project, the 5-DoF table can accommodate the dimensions and weight of an SXT flight (60°) section (Figure 2). This objective and the need to support test articles from above (Figure 6, §4.1) resulted in a hefty structure (Figure 7).

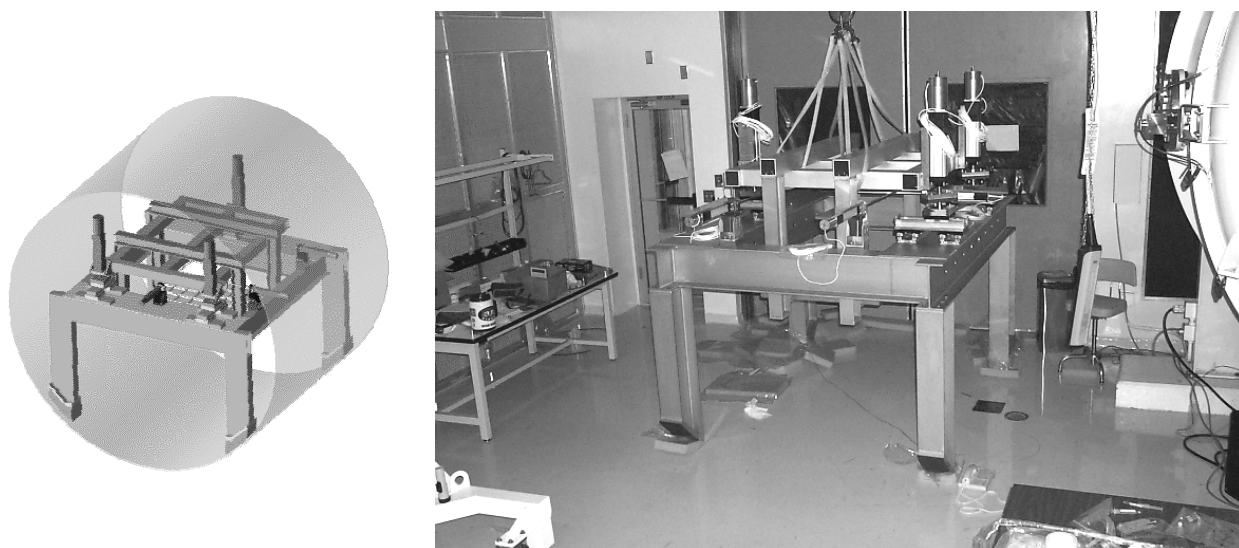


Figure 7 — Structure of the 5-DoF optics mount. Left panel shows a schematic drawing of the Mount structure and its location within the 100-m facility's instrument chamber; right panel shows the nearly fully assembled 5-DoF Mount structure. Test articles attach through interface hardware to the bottom of the 5-DoF table.

The 5-DoF mount provides three (3) translational degrees of freedom, over a range of ± 75 mm at 25- μ m resolution in each direction. Installation of the 5-DoF mount into the chamber will align these translational axes to be longitudinal (parallel to the facility optical axis) and transverse horizontal and vertical. In addition, the 5-DoF mount affords two (2) rotational degrees of freedom, over a range of $\pm 3^\circ$ at 5" resolution. The 5-DoF control system will assign these to be yaw (rotation about the vertical axis) and pitch (rotation about the transverse horizontal axis). Owing to the design of the 5-DoF and its control system, the mount is actually quasi-6-DoF, with limited roll (rotation about the longitudinal axis). The mount's control system utilizes actuators and encoders wired via vacuum feedthroughs to a control cabinet outside the chamber. LabView™ Virtual Instrument software drives the controllers, to provide precise translation and rotation about the position of the optical node of the test article.

A costly (in time and money) lesson of fabricating the 5-DoF mount has been dealing with contamination introduced by purchased components sold as "vacuum compatible". Due to the sensitivity of optics to molecular and particulate contamination, MSFC has very stringent contamination-control requirements for hardware used in its space-optics test chambers. For flight optical systems, there are similarly tight requirements on purchased hardware. In an effort to reduce costs for the non-flight development optics, we attempted to utilize commercially available "vacuum compatible" hardware. Unfortunately, some of the "vacuum compatible" components contained hydrocarbon lubricants, plastic parts,

wiring insulation, etc. that are unacceptable in the vicinity of optically sensitive surfaces. Consequently, we experienced much frustration in attempting to certify the cleanliness of all components going into the instrument chamber. Several purchased components required disassembly, precision cleaning, re-assembly, bake-out, and re-certification runs.

4.3 Optics subsystem

The Optics subsystem encompasses all the hardware attached to the mount. The initial test article will be the Optical Alignment Pathfinder Two⁷ (OAP2), designed and built by GSFC. For exercising the GSE hardware and rehearsing test procedures, GSFC is providing a surrogate optic, populated with a pair (primary and secondary) of coated reflectors that do not have precision replicated surfaces.

The OAP2 (Figure 8, left) is a test bed for developing procedures for aligning and bonding x-ray mirrors, using the

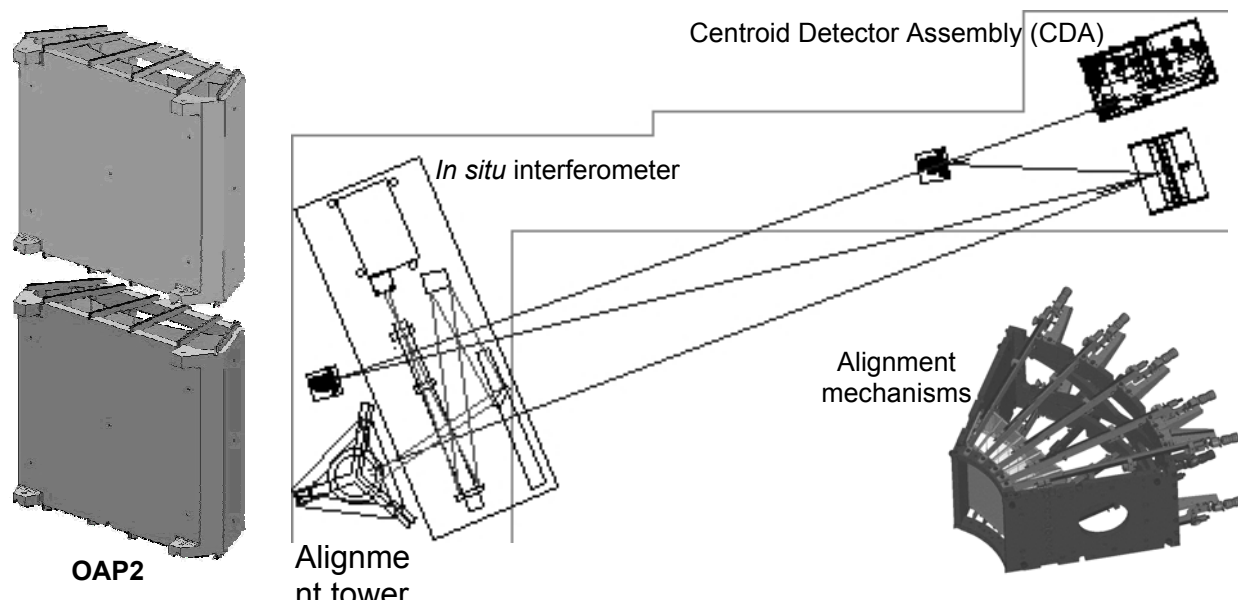


Figure 8 — Optical Alignment Pathfinder Two (OAP2) and alignment and metrology hardware. Left drawing displays the OAP2 (without its 4 connecting bars). The lower right drawing shows the OAP1, which provides the framework for aligning and bonding mirrors in the OAP2. The remainder of the figure schematically illustrates the alignment configuration at GSFC.

OAP1 (Figure 8, lower right) alignment mechanisms. The GSFC alignment configuration (Figure 8) utilizes the Centroid Detector Assembly (CDA) — previously used to align the *Chandra* (nee AXAF) mirrors into its high-resolution mirror assembly. The CDA is a pointed laser-beam system, with beam-splitter hardware and quad-cell photodiode detector. By positioning the CDA such that the virtual light source and the photodiode's center are both at the focal position of the x-ray optic, one aligns the mirror such that the return beam is centered on the quad-cell detector. In addition to the CDA alignment, the GSFC configuration allows *in situ* interferometric metrology⁸ of the mirror during the alignment and bonding processes. The OAP2 comprises two annealed-titanium housings — one for primary mirrors, the other for secondary mirrors — connected by 4 titanium struts bonded to the housings. By using a suitable titanium alloy, the coefficient of thermal expansion (CTE) of the housing closely matches that of the glass mirrors. Furthermore, the housing is more massive than a flight-like housing in order to provide a sufficiently stiff structure to isolate intrinsic mirror-quality, distortion, and alignment issues from gravitationally induced distortions of the housing.

Besides the OAP2 itself, the Optics subsystem includes ancillary hardware (Figure 9), designed and fabricated by SAO. This hardware includes a test box which houses the OAP2 and serves as a heater box providing a thermally controlled environment for the temperature-sensitive optics assembly. The test box rests on a support stand and structure that attaches to and hangs from the 5-DoF table. Within the test box is a drive for an aperture wheel, which delimits the azimuthal extent of the aperture and provides smaller azimuthal slits for sub-aperture sampling of the test optic. In addition, reference flats and fiducial markings will facilitate alignment of the test article to the facility optical axis.

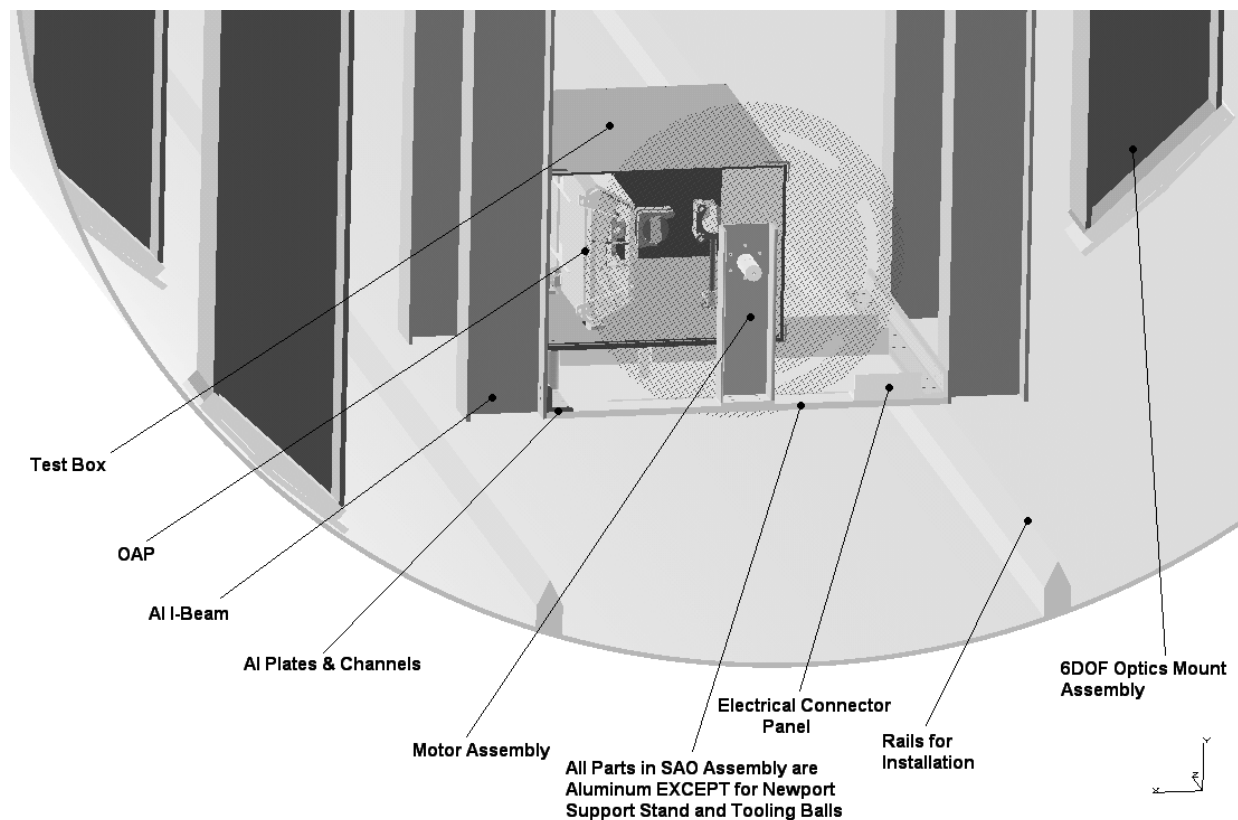


Figure 9 — Ancillary hardware for the Optics subsystem. The drawing shows the SAO-fabricated test (heater) box enclosing the OAP2, the aperture wheel for sampling the OAP2 mirrors, and support structure for interfacing to the 6-DoF mount within the instrument chamber.

Although the OAP2 was designed to have low sensitivity to temperature offsets and gradients, thermal-mechanical analyses (Figure 10) demonstrate the necessity of active temperature control for the x-ray performance testing. Consequently, SAO designed and fabricated a thermal control system for the OAP2. The thermal-control system includes a 6-sided, aluminum heater box (Figure 9) with 2 heater strips per side, covered with multi-layer insulation (MLI). The electronics provide 3-zone temperature control, using Minco™ controllers and resistance temperature detector (RTD) sensors. In addition, a data-acquisition computer monitors and logs the temperature of 30 thermistors, at various locations on the OAP2 housing and the heater box, through Sensoray™ data-acquisitions boards. All controllers, power supplies, data-acquisition boards, etc. reside outside the instrument chamber and are connected to the heater strips, RTDs, and thermistors with wiring utilizing the facility's feedthrough ports.

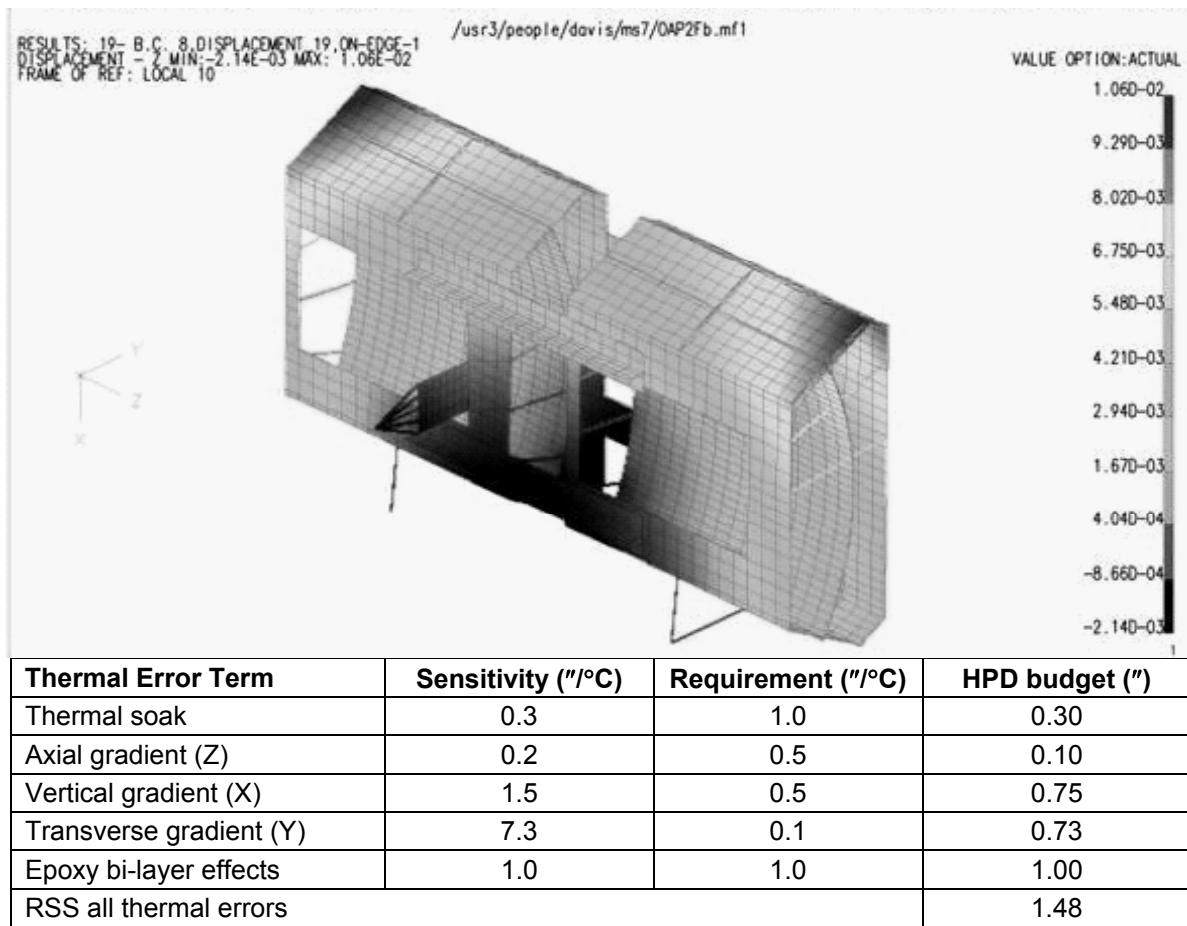


Figure 10 — Sensitivity to temperature and temperature gradients. Upper panel illustrates mechanical distortions due to temperature gradients. Lower panel summarizes sensitivity of the half-power diameter (HPD) to temperature, temperature gradients, and epoxy bi-layer effects.

An aperture wheel masks the azimuthal extent of the OAP2 to selectable 50°, 40°, or 30° apertures. It also provides interchangeable 6°, 4°, or 2° sub-apertures for sampling the optic azimuthally. A 20 step/rev Phytron™ stepper motor provides 0.36° (1000 step/rev) resolution through a 50:1 planetary gearbox. The aperture-wheel control electronics employs a Hall-effect home sensor and an Intelligent Motor Systems™ indexer (in a rack outside the chamber).

4.4 Source subsystem

Currently, the Source subsystem at the 100-m facility provides only (electron-impact) fixed-anode sources. Those sources are a TruFocus™ high-energy (125 kV peak) source, TruFocus™ and Kevex™ medium-energy (50 kV peak) sources, and a Manson low-energy (15 kV peak) source. Each has a set of interchangeable (anode) targets, thus providing various atomic x-ray fluorescence lines. The medium-energy sources have small spot sizes (from less than 0.2 mm to 1 mm) and are easy to install and use, especially since they are self-contained, closed systems. However, the price of this convenience is that their beryllium windows are opaque to x rays below about 4 keV.

Although very smooth, precision Zerodur™ mandrels fabricated by Zeiss⁹ will be used to replicate later mirror sets, metal mandrels will be used for initial mirror sets. Consequently, the initial optics will have relatively poor surfaces, due to degradation of metal mandrels after multiple replications. To reduce diffractive scattering by surface microroughness and allow measurement of the *geometric* half-power-diameter, we shall conduct initial performance testing at a relatively

low x-ray energy. Consequently, for the OAP2 rehearsal and eventual performance tests, we shall use the Manson source (Figure 11) with an aluminum target, which gives a strong Al-K α line at 1.49 keV. For the source distance of nearly 100 m, the 1-mm spot size corresponds to a 2" source, sufficiently small for initial performance testing. Because the current Detector subsystem (§4.5) utilizes a front-illuminated CCD, it is not feasible to use a lower energy x-ray line. Furthermore, the current CCD is too slow for photon counting and will, thus, be used for collected-charge imaging. In order to achieve the necessary spectral purity, we shall operate the source at an anode voltage only 2 or 3 times the Al-K-shell ionization potential (1.56 kV) and employ a 20- μ m-thick Al filter to attenuate effectively x radiation away from the Al-K α line (Figure 11). The aluminum filter also serves as an optical blocking filter.

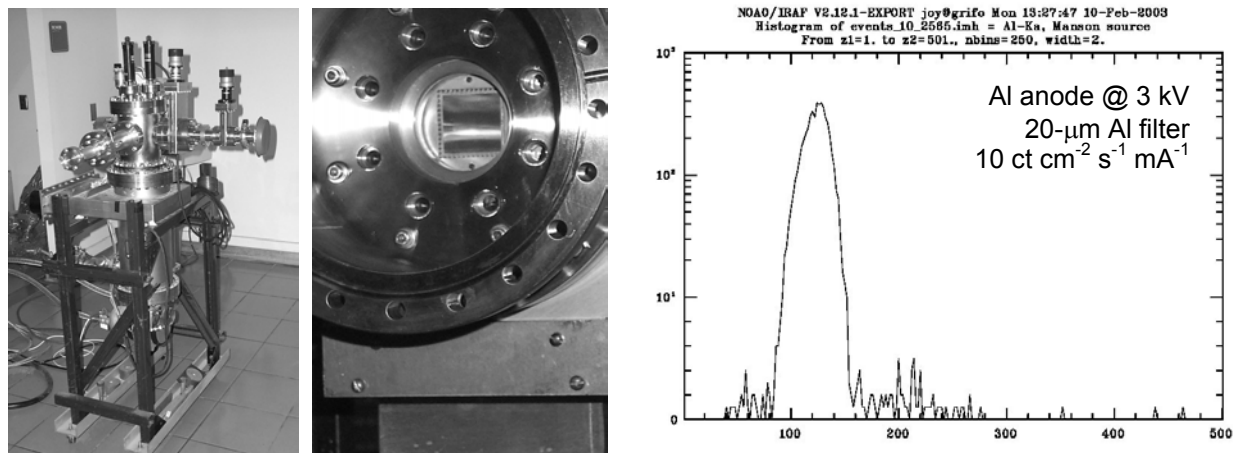


Figure 11 — Source-detector combination for OAP2 rehearsal and testing. Left photo displays the Manson x-ray source; right photo, the large-format CCD camera. The plot confirms spectral purity for an Al anode operated at 3 kV with a 20- μ m Al filter.

4.5 Detector subsystem

The Detector subsystem for OAP2 testing is an x-ray camera comprising a large-format (37-mm-square) Loral™ 2048×2048 front-illuminated CCD (Figure 11). The spatial resolution (18 μ m) and field of view are excellent, corresponding to 0.4" and 13', respectively, for image distances of the order 10 m. Employing an Infrared Laboratories™ LN2-cooled cryostat, the CCD has relatively low dark current. In addition to being front-illuminated, another major (perhaps more significant) disadvantage of the camera is its slow electronics, interfaced via an S-bus controller to a Sun™ Sparcstation 5 for instrument control and data acquisition. With a read-out time of about 100 s, it is not efficient to use the camera for photon counting, due to potential pile up of focused images. Consequently, we require and will provide a spectrally pure x-ray source (Figure 11), to permit image analysis using collected charge (rather than events). The well capacity of a CCD pixel is about 97 ke⁺, corresponding to 356 keV or 240 Al-K α photons.

4.6 Data subsystem

The Data subsystem acquires the images from the CCD camera and stores them in Flexible Image Transport System (FITS) format, a standard format in the astronomical community. We shall then distribute the test data to the SXT team members for conducting independent analyses of optical performance.

5. TEST PLANS

Prior to x-ray testing an optic, we shall conduct a test rehearsal with the OAP2 surrogate article. The first purpose of the rehearsal is to practice and document procedures for installation, alignment, and operation; the second, to exercise hardware (5-DoF mount, aperture wheel, thermal control) in the vacuum environment; the third, to practice and document procedures for performance testing and data analysis. X-ray test operations include beam finding, focus finding, on- and off-axis imaging, subaperture sampling (with aperture wheel), and intrafocal (ring-segment) imaging.

Figure 12 schematically illustrates the optimal configuration for testing an azimuthal section of an optic. For the Stray-Light Facility's 104.576-m source–detector distance (d) and the OAP2's 8.400-m focal length (f), the finite-conjugate image distance (i) is 9.211 m and the object distance (o) is 95.365 m. In order to fully sample the optic, it is necessary to tilt it about its node such that the average ray is normal to the entrance aperture. (Otherwise rays reflecting from the front part of the primary would miss the secondary and thus not be imaged.) This is achieved when the OAP2 axis is oriented such that the source lies about the optic's radius away from the optic's axis. For the OAP2's approximately 0.25-m radius, this corresponds to an 8.9' tilt of the OAP2 axis with respect to the facility optical axis.

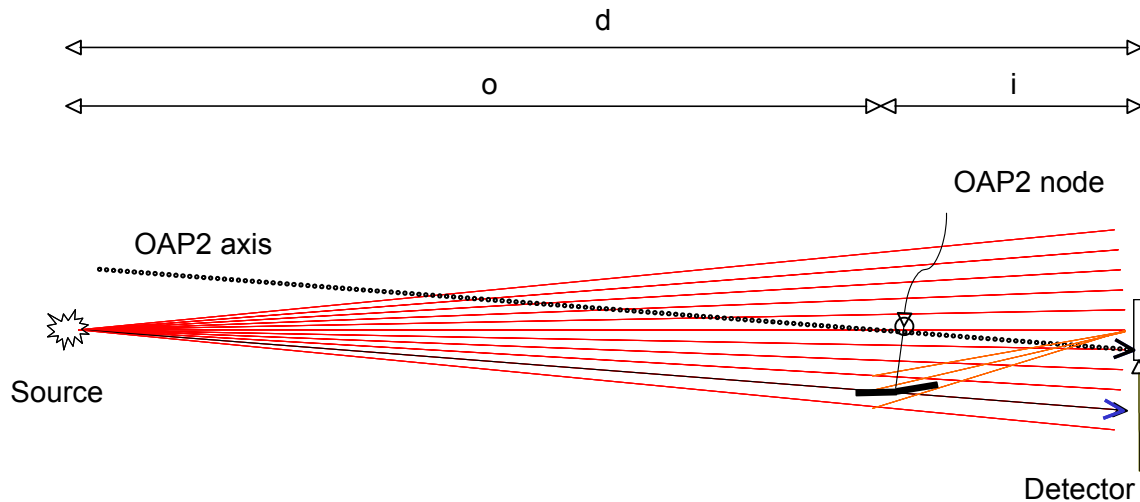


Figure 12 — Test configuration for testing segmented optics. Best focus occurs at finite-conjugate image distance; maximum sampling of the primary mirror requires tilting the segmented optic so that the mean ray is nearly normal to the entrance aperture.

Upon completion of the GSE hardware, we shall conduct a test rehearsal with the OAP2 surrogate in late 2003. We anticipate beginning x-ray performance testing of SXT (and HXT) development optics in mid 2004.

REFERENCES

- ¹ N.E. White & H.D. Tananbaum, “Constellation-X mission: science objectives and implementation plan”, Proc. SPIE, **4851**, 293–303, 2003.
- ² M.C. Weisskopf, B. Brinkman, C. Canizares, G. Garmire, S. Murray, & L.P. Van Speybroeck, “An overview of the performance and scientific results from the Chandra X-Ray Observatory”, Pub. ASP, **114**, 1–24, 2002.
- ³ M.C. Weisskopf, “Four years of operation of the Chandra X-Ray Observatory”, Proc. SPIE, **5165**, in press.
- ⁴ R. Petre, “Recent progress on the Constellation-X spectroscopy x-ray telescope (SXT)”, Proc. SPIE, **5168**, in press.
- ⁵ W.W. Zhang, D.A. Content, T.T. Saha, R. Petre, S.L. O’Dell, W.D. Jones, W.N. Davis, & W.A. Podgorski, “Development of x-ray reflectors for the Constellation-X observatory”, Proc. SPIE, **5168**, in press.
- ⁶ S.L. O’Dell & M.C. Weisskopf, “Advanced X-ray Astrophysics Facility (AXAF): calibration overview”, Proc. SPIE, **3444**, 2–18, 1998.
- ⁷ S.M. Owens, J.J. Hair, J. Stewart, R. Petre, W.W. Zhang, W.A. Podgorski, P. Glenn, D.A. Content, T.T. Saha, & G. Nanan, “The Constellation-X SXT optical alignment pathfinder 2: design, implementation, and alignment”, Proc. SPIE, **5168**, in press.
- ⁸ D.A. Content, D. Colella, C. Fleetwood, T. Hadjimichael, T.T. Saha, G. Wright, & W.W. Zhang, “Optical metrology for the segmented optics on the Constellation-X spectroscopy x-ray telescope”, Proc. SPIE, **5168**, in press.
- ⁹ W.J. Egle, W. Hafner, A. Matthes, G. Wilma, A. Ilg, & H. Schiele, “Fabrication of segmented Wolter type-1 mandrels for the Constellation-X mirror-development program”, SPIE, **5168**, in press.